Mangroves shelter coastal economic activity from cyclones

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Mangroves shelter coastlines during hazardous storm events with coastal communities experiencing mangrove deforestation are increasingly vulnerable to economic damages resulting from cyclones. To date, the benefits of mangroves in terms of protecting coastal areas have been estimated only through individual case studies of specific regions or countries. Using spatially referenced data and statistical methods, we track from 2000 to 2012 the impact of cyclones on economic activity in coastal regions inhabited by nearly 2,000 tropical and subtropical communities across 23 major mangrove-holding countries. We use nighttime luminosity to represent temporal trends in coastal economic activity and find that direct cyclone exposure typically results in permanent loss of 5.4–6.7 mo for a community with an average mangrove extent (6.3 m per meter of coastline); whereas, a community with more extensive mangroves (25.6 m per meter of coastline) experiences a loss equivalent to 2.6–5.5 mo. These results suggest that mangrove restoration efforts for protective benefits may be more cost effective, and mangrove deforestation more damaging, than previously thought.

ecosystem services | global spatial analysis | mangroves | natural disaster | storm protection

Mangroves shelter coastlines during storm events by reducing water flow pressure, surge height, flooding levels and durations, wind velocity, and saline water intrusion (1–4). To date, the benefits of mangroves in terms of protecting physical property, local agriculture and industry, and lives in coastal areas have been estimated only through individual case studies of specific regions or countries (3–8). Here, we conduct a more comprehensive global analysis of over 200 million individuals spread across 23 countries to determine whether these storm protection services extend to a greater range of representative coastal communities worldwide. We focus on whether the presence of mangroves mitigates permanent loss of economic activity as indicated by changes in nighttime luminosity in coastal communities due to direct cyclone exposure. In addition, we estimate the extent to which protection of coastal economic activity is affected by differences in mangrove extents found along coastlines. The results are especially critical to determining the role of natural infrastructure in shielding coastal communities against climate change and hazardous storm events (9–13).

Nighttime lights products have been used to measure trends in economic activity, such as gross domestic product (14, 15). These products are particularly useful in areas that lack high quality (16) or highly local (17) administrative data on economic accounts. The temporal resolution of nighttime lights suits the product well for assessing the impacts of natural disasters. For example, ref. 18 shows that nighttime lights capture wind-related damages in cyclone-exposed communities, but may not capture destruction stemming from storm surge. In the case of Tropical Cyclone Pam, exposed areas returned to full luminosity within 8–10 mo with a cumulative increase in luminosity, presumably driven by disaster aid and postdisaster recovery activities, experienced 12 mo later. The longer run effects of cyclone exposure on economic activity and the extent to which mangroves can shelter such economic activity remain poorly understood.

Over the final 2–3 decades of the twentieth century, ∼35% of global mangrove cover was converted with annual loss rates of 2.1% (13, 19). From 2000 to 2012, global mangrove deforestation slowed to ∼0.3% annually, but deforestation was about double the global average in Southeast Asia (20). Mangrove losses have been driven by commercial aquaculture expansion, harvesting of wood products, freshwater diversion, urbanization, and other coastal developments (13, 19–22), which in turn have left many coastal communities vulnerable to the economic damages of hazardous storm events, such as cyclones (5, 6, 9–13). Therefore, a global analysis of the extent to which the storm protection services foregone with mangrove losses impact coastal communities economically is important for fostering mangrove conservation and restoration efforts worldwide (23–26).

Results

Of the estimated 208 million individuals affected by cyclones, ∼184 million (88.2%) are in 18 developing countries with a gross national income (GNI) per capita less than $12,476. Of these, we estimate that over 50% or nearly 98 million are in 10 low- or lower-middle-income countries with a GNI per capita less than $4,036 (Table 1). Thus, our analysis is relevant to coastal communities in some of the poorest economies in the world, where the natural protection provided by mangroves to local economic activity may be especially relevant given the lack of alternative, human-built infrastructure (10–13). To focus on this potential protective role, we present our results for two types of coastal communities in our sample: a coastal community with the average

Significance

Mounting evidence suggests that mangrove forests protect coastal communities during tropical storm events. Yet, no large-scale analysis exists documenting these storm protection benefits globally. We provide global evidence that mangroves shelter economic activity during tropical cyclone exposure and that this sheltering prevents otherwise permanent losses to economic activity. These findings reveal that even modest mangrove forest coverage has the capacity to provide tremendous storm protection services, which highlights the need for mangrove conservation in many vulnerable coastal communities that have prior received less attention.

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Table 1. **Annually averaged and aggregated cyclone and mangrove summary statistics (2006–10)**

Country	Growth	Population (thousands)	Exposed population (thousands)	Population exposed (share)	Mangrove area (ha)	Mangrove protected area (ha)	Mangroves protected (share)
Bahamas	0.12	268	50	0.19	155.7	0.2	0.00
Belize	0.14	123	58	0.47	1,684.0	76.9	0.05
China	0.13	71,600	61,000	0.85	178.5	70.4	0.39
Colombia	0.14	2,820	0	0.00	1,688.0	1,006.0	0.60
Costa Rica	0.16	30	6	0.20	2.6	2.6	1.00
Cuba	0.18	3,360	1,580	0.47	3,920.0	1,582.0	0.40
Dominican Republic	0.09	814	320	0.39	122.6	64.4	0.53
El Salvador	0.12	460	4	0.01	1,310.0	1,258.0	0.96
Fiji	0.14	191	0	0.00	266.0	12.0	0.05
Guatemala	0.19	617	214	0.35	1,502.0	1,088.0	0.72
Haiti	0.28	477	227	0.48	4.9	0.0	0.00
Honduras	0.15	374	118	0.32	1,000.0	788.0	0.79
Hong Kong	0.02	1,252	997	0.80	20.7	13.3	0.64
India	0.14	83,200	955	0.01	1,972.0	376.0	0.19
Japan	0.04	1,293	554	0.43	9.7	6.6	0.68
Madagascar	0.17	392	140	0.36	29.3	0.0	0.00
Mexico	0.11	7,100	2,720	0.38	11,580.0	6,600.0	0.57
Mozambique	0.16	2,960	378	0.13	166.6	0.0	0.00
Nicaragua	0.16	135	27	0.20	770.0	312.0	0.41
Philippines	0.15	5,380	1,674	0.31	724.0	90.7	0.13
Trin. and Tob.	0.13	495	0	0.00	133.3	4.3	0.03
United States	0.07	21,200	10,720	0.51	12,160.0	10,920.0	0.90
Vietnam	0.15	3,820	2,240	0.59	1,232.0	832.0	0.68
LOW	0.17	3,829	746	0.19	201	0	0.00
LM	0.14	93,985	5,232	0.06	8,510	4,745	0.56
UM	0.13	86,037	65,684	0.76	19,442	9,414	0.48
EA&P	0.13	83,536	66,465	0.80	2,431	1,025	0.42
LA&C	0.14	17,071	5,325	0.31	23,873	12,782	0.54
NA	0.07	21,200	10,720	0.51	12,160	10,920	0.90
SA	0.14	83,200	955	0.01	1,972	376	0.19
SSA	0.16	3,352	518	0.15	196	0	0.00
Developed	0.06	24,507	12,321	0.50	12,479	10,944	0.88
Developing	0.13	183,851	71,662	0.39	28,152	14,159	0.50
Total	0.13	208,359	83,983	0.40	40,632	25,103	0.62

The sample includes all mangrove-holding LLAs within those 22 countries and 1 territory (Hong Kong) that passed within 100 km of a cyclone's "eye" from 2006 to 2010. The panel spans from 2000 to 2010 and sample statistics are reported for 2006–2010, which remain in sample using our lagged specification. Income group aggregates are presented based on the 2016 world bank classifications. Low income countries (LOW) have a gross national income (GNI) per capita<\$1,025, lower middle-income countries (LM) between \$1,026 and \$4,035, upper-middle income countries (UM) between \$4,036 and \$12,475. Developing countries include all LOW, LM, and UM income countries and developed countries have a GNI per capita of \$12,476 or more. East Asia and Pacific (EA&P), Latin America and Caribbean (LA&C), North America (NA), South Asia (SA), and Sub-Saharan Africa (SSA) regional aggregates are also presented based on World Bank categorizations.

seaward-to-inland mangrove extent of our sample, and a community with a more expansive mangrove width (one SD above the average extent).

We use the 1 arc-second (~30 m resolution at the equator) continuous global mangrove forest cover for the twenty-first century dataset to find that the average coastal community in our sample has 6.3 m of mangroves extending inland from the seaward edge per meter of coastline, which is computed by dividing each village's total mangrove extent area from the village's seaward limit by the village's coastline length. To examine the sheltering effect of mangroves on coastal economic activity, we compare two cases of simulated cyclone exposures in (*i*) a representative community with a sample average mangrove extent (6.3 m per meter of coastline) and (*ii*) a community with a sample SD increase in mangrove extent above the sample mean (25.6 m per meter of coastline). Basing the simulation on sample SDs ensures that our findings are representative of the global population receiving storm protection benefits from mangroves. Within our sample, we estimate that over 27 million individuals lived in coastal communities each year with at least 6.3 m of mangroves per meter of coastline of which ~43% lived in communities with at least 25.6 m of mangroves per meter of coastline.

Following direct cyclone exposure, the representative community suffers a cumulative 6.1–8.2% drop in the growth rate of economic activity as proxied by trends in nighttime luminosity using the Defense Meteorological Satellite Program dataset. This disruption translates to a permanent loss of 5.4–6.7 mo in economic activity (Fig. 1) when using a 95% confidence band and to the extent that these disruptions are represented by variation in nighttime luminosity. These estimated impacts on economic activity are robust to a variety of autoregressive processes and empirical specifications (Table 1 and *SI Appendix*, Table S1). After 6 y, the growth rate of economic activity in cyclone-exposed communities tapers off along a path parallel to prestorm rates, which is the dotted line indicated in Fig. 1. This suggests that a representative coastal community with a relatively narrow width of mangroves suffers permanent setbacks in economic activity, which may not recover to prestorm levels for a substantially long period of time.

In comparison, economic activity for a community with 25.6 m of mangroves extending inland per meter of coastline are more

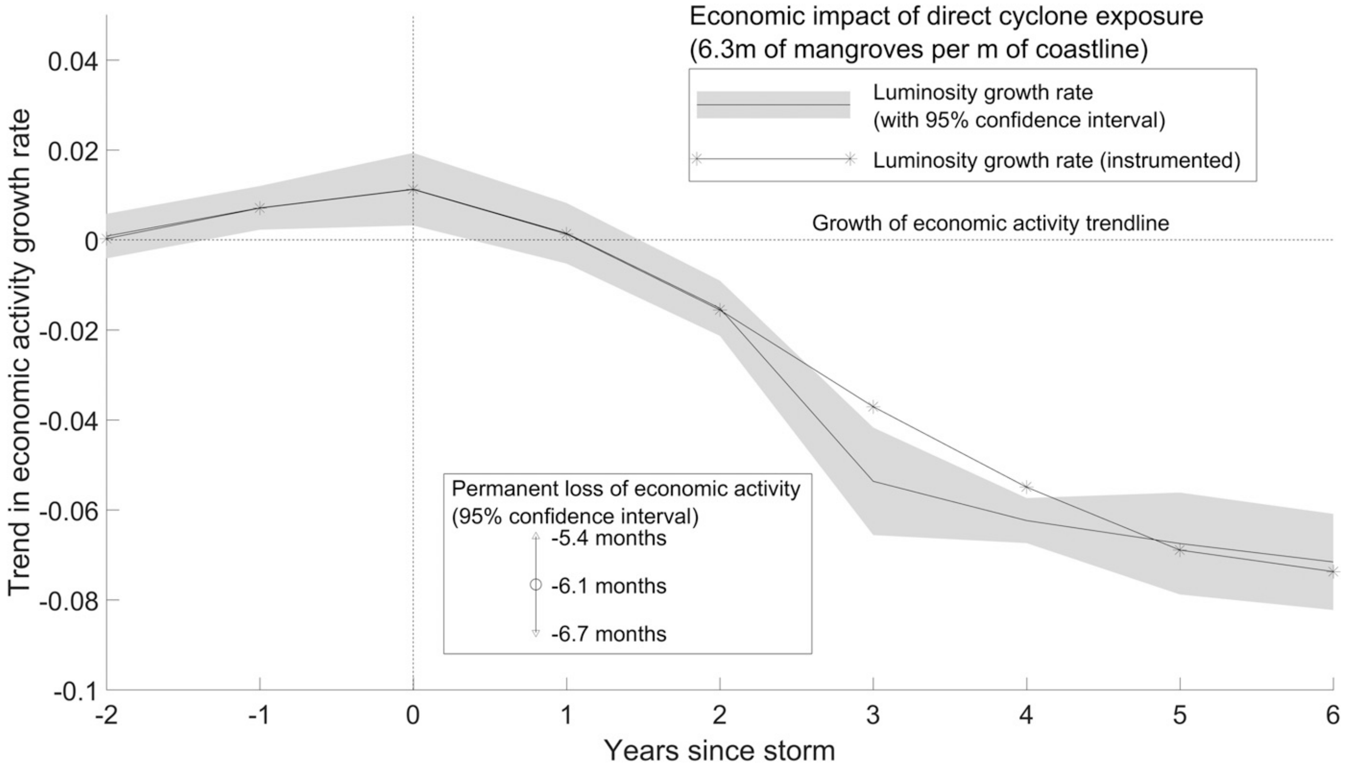

Fig. 1. Economic impact of cyclone exposure (6.3 m of mangroves per meter of coastline). Cyclone exposure occurs in year 0. Shaded areas represent 95% confidence intervals around the cumulative impact of cyclone exposure on the trend in economic activity growth rate. The solid line represents estimates from the ordinary least squares (OLS) specification and the line with asterisks represents two-stage least squares estimates instrumented using the width of mangroves located in protected areas, which are less likely to be converted during postdisaster recovery. Both estimates are evaluated at the sample mean mangrove width (6.3 m per meter of coastline).

sheltered from storm exposure (Fig. 2). For this community, growth in economic activity still declines—between 3.0% and 6.4% due to direct cyclone exposure—which translates to a permanent loss of 2.6–5.5 mo when using a 95% confidence range. Like a representative community, after 6 y, the growth rate of economic activity in a cyclone-exposed community tapers along a path parallel to prestorm rates, which is the dotted line indicated in Fig. 2, adversely affecting livelihoods for years to come.

We do not detect an immediate impact on economic activity in the year following cyclone exposure. Consistent with previous work, the absence of an immediate effect on luminosity likely results from offsetting effects of wind destruction and postdisaster aid and recovery activities (18). However, the persistent decline in luminosity in the years following the storm suggests that the impact of cyclones on coastal economic activity remains after recovery activities have concluded.

Further, we might expect an inflow of capital and labor into cyclone-exposed areas as the returns on capital investment increase in disaster-torn communities—i.e., "recovery to trend hypothesis" (see ref. 27 for a review of competing hypotheses of the impact of cyclones on economic growth). Rather, our results are consistent with a "no recovery" scenario where productive capital, such as roads, buildings and schools, and durable goods are destroyed, and postdisaster aid and investment postpone but do not prevent luminosity-based detection of long-term and adverse effects on economic activity.

If disaster-torn coastal communities increase mangrove conversion activities during the economic recovery phase, then our estimates of how the presence of mangroves reduces storm damages may be overstated. To control for this problem, we use an instrumental variable approach that leverages the fact that mangroves in protected areas are less likely to be converted during postdisaster recovery and are plausibly protected from these recovery activities (28). For each village, we construct an equivalent mangrove width distance measure (meters of protected mangroves per meter of coastline) based on mangroves that are located exclusively in protected areas (shown in Figs. 1 and 2) as indicated by the World Database on Protected Areas, which is inclusive of United Nations biosphere reserves, community protection schemes, and Ramsar sites.

In applying this estimation approach to both the representative community with average mangrove extent and the community with more expansive mangroves, we are unable to identify a statistically significant difference in poststorm economic activity growth rates (Figs. 1 and 2). There is also no statistically significant change in an exposed community's rate of mangrove deforestation before and after storm events (Fig. 3). Together, these two findings suggest poststorm recovery is driven by the initial sheltering capacity of mangrove forests rather than any subsequent mangrove deforestation during the recovery phase. However, we cannot determine the extent to which mangrove presence itself creates a signal of future storm protections that influences capital inflows in the years after a cyclone. In such a case, communities sheltered by expansive mangroves may be perceived as lower risk than communities with less expansive mangroves, and resulting investments into these areas may aid in the attenuation of otherwise permanent losses to economic activity.

In conclusion, we provide global evidence across multiple countries and coastal communities that mangroves shelter economic activity affected directly by cyclones. Our results are notable for three reasons. First, our findings support the growing number of studies that underscore the importance of natural infrastructure to shield vulnerable coastal communities from the coastal hazards associated with climate change, especially in

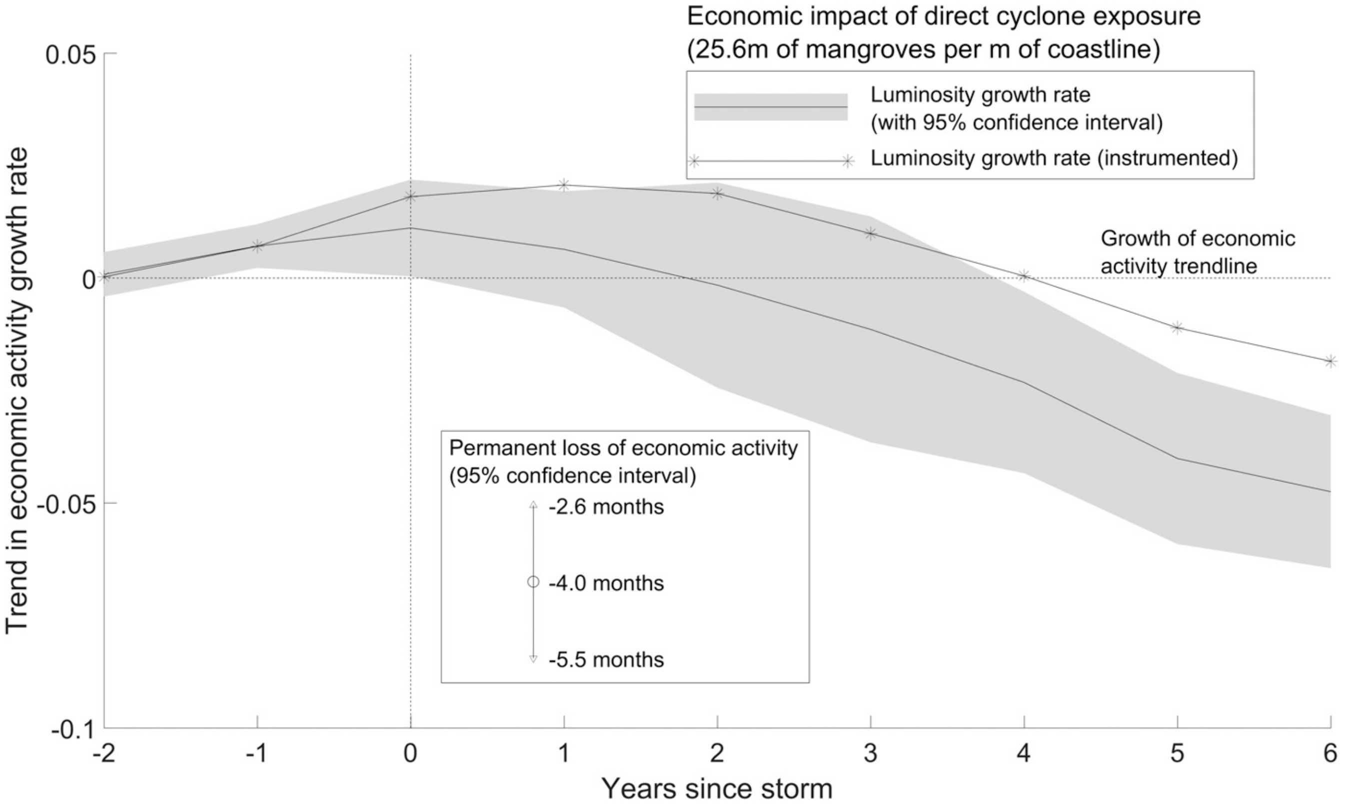

Fig. 2. Economic impact of cyclone exposure (25.6 m of mangroves per meter of coastline). Cyclone exposure occurs in year 0. Shaded areas represent 95% confidence intervals around the cumulative impact of cyclone exposure on the trend in economic activity growth rate. The solid line represents estimates from the OLS specification and the line with asterisks represents two-stage least squares estimates instrumented using the width of mangroves located in protected areas, which are less likely to be converted during postdisaster recovery. Both estimates are evaluated at the sample mean mangrove width + 1 sample SD (25.6 m per meter of coastline).

developing countries (9–13). Second, mangrove deforestation has occurred rapidly over the past several decades (13, 19, 20), and our analysis offers confirmation for the many community-led conservation and restoration efforts worldwide that require a better understanding of the storm protection services foregone with mangrove losses (23–26). In fact, our results indicate that coastal communities with only modest mangrove coverage still receive substantial storm protection benefits, which suggest that restoration efforts may be more cost effective and mangrove deforestation more damaging than previously thought (29, 30). Finally, our analysis and evidence replicate at the global scale findings from specific case studies that have demonstrated at the country and regional level that mangroves generate valuable storm protection services in coastal communities that are vulnerable to direct cyclone exposure (1–8). Future work should focus on explaining the mechanism by which mangrove presence limits permanent economic losses in coastal communities that experience cyclones. Critical to this work will be assessing the importance of mangroves in buffering coastal communities from physical storm exposures, such as high winds and storm surge, relative to the role of mangrove presence as a risk signal that attracts postcyclone capital investments into those areas perceived to be "sheltered" against future storm exposures.

Data and Methods

We construct an annual panel dataset from 2000 to 2012 of 1,928 coastal communities within 23 cyclone-exposed countries that contain 194 mangrove-holding provinces. The scope of similar analyses has been limited by data

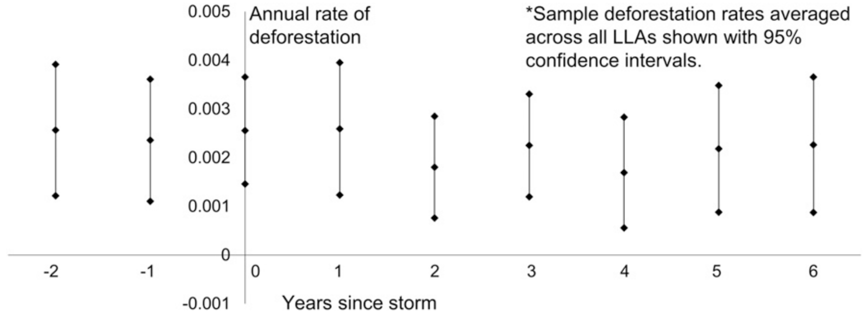

Fig. 3. Storm events and mangrove deforestation rates for sample LLAs with 95% confidence intervals. The annual rate of deforestation is calculated as the percentage of mangrove coverage loss annually. Cyclone exposure occurs in year 0. Here, sample deforestation rates are presented before, during, and after direct storm exposure with 95% confidence bands.

availability for economic outcomes, which tend to lack either depth (one country with subnational coverage from a survey) or breadth (many countries relying on comparable national accounts). We employ global nighttime lights data to document trends in economic activity before and after storm events. Using luminosity data allows us to construct highly local measures of economic output that are comparable on a global scale. Annual and global high-resolution mapping of mangrove forests and cyclone paths are also used in our analysis. Data resolution plays a central role in our empirical strategy, which, in the vicinity of a storm event, relies on local variation in the width of mangrove forests as they extend from the seaward edge and intensity of storm exposure. Additional information on our data sources and geospatial processing are available in the *SI Appendix*.

We define a coastal community as the country's lowest-level administrative (LLA) delineation that is immediately adjacent to a coastline. Our mangrove data span from 2000 to 2012 despite other variables being available for earlier and later years. Summary statistics (Table 1 and *SI Appendix*, Table S1) are based on in-sample annual averages from 2005 to 2010, whereas earlier and later years are dropped as lags in our empirical specifications. The sample captures over 200 million individuals in coastal communities that were located within 100 km of a cyclone's "eye" in a given year, and thus likely experienced maximum wind velocity and surface pressures (31). A new high-resolution database of mangrove forest cover is aggregated to find each coastal community's extent of mangrove forests from the community's seaward edge, the density within protected areas and the community's average elevation (20). We remove from our sample communities with mangroves in excess of 250 m per meter of coastline, which represent outlier cases less representative (<1% of sample) of where storm protection services are likely to be generated. Empirically, these outlier communities would otherwise drive results but are less relevant in the purview of a global analysis. Further, the protective role of mangroves in such case areas has been the topic of many prior studies. We also restrict our sample to those communities with an average elevation <100 m that were therefore likely to have unfettered access to mangrove forests and lack other topographic protections against storm exposure.

The growth rate in average annual luminosity from nighttime lights, which has been shown to trend closely with economic growth, is measured as a proxy for each community's economic activity (14, 15, 32). We describe disruptions in the trend of nighttime lights relative to a year of growth in nighttime lights, which provides an estimate of the months that permanent loss in economic activity occurs relative to its original trend line (*SI Appendix*). Measuring a disruption to economic activity relative to its trend acts as a normalization that makes our measurements more comparable to other conventional indicators of economic activity, such as gross domestic product and gross national income. Such interpretation is necessary because luminosity growth rates trend with but generally exceed economic growth rates (14, 15).

We use a distributed-lag autoregressive model to examine the impact of direct cyclone exposure on growth in coastal community economic activity (25, 26). Direct cyclone exposure occurred if a cyclone passed within 100 km of any coastal community's nearest border. We define coastal communities as the LLA units within each country that are available in georeferenced form and contain a seaward coastline. The growth in economic activity for each coastal community is defined as the percentage change in luminosity as measured using nighttime lights data and approximated as the difference in logs between years, $growth = \ln(luminosity_t) - \ln(luminosity_{t-1})$. Our estimating equation is

$$growth_{i,j,t} = \sum_{L=0}^{n}\left[\beta_L \ x \ C_{i,j,t-L}\right] + \gamma_j + \delta_t + \theta_{i,t} + \eta X_{i,j,t} + \epsilon_{i,j,t} \qquad [1]$$

where the vector of β coefficients capture the marginal effects of direct cyclone exposure on the growth rate of luminosity for the *j'th* administrative unit, within country *i*, and in time period $t - L$, where *t* is the observed year and L is the number of lags ranging from 0 to *n*. Growth trends in luminosity specific to each administrative unit are captured by γ while deviations in growth rates for each year are captured by δ. Country–year-specific shocks to growth are captured by θ. For each administrative unit, observable characteristics that may influence luminosity growth are controlled for in a vector of control variables, $X_{i,j,t}$. SEs are clustered at the cyclone basin level to allow for arbitrary serial correlation across administrative units within the same cyclone paths, as defined by the National Oceanic and Atmospheric Administration's Atlantic Oceanographic and Meteorological Laboratory (AOML) Physical Oceanography Division (1).

The impact of a cyclone on long-run trends in economic activity *z* years later is

$$\Lambda_{i,j} = \sum_{L=0}^{z}\left[\beta_L\right],$$

which is the cumulative effect (summation of marginal effects) of cyclone exposure on luminosity growth. We expand our estimating equation

$$\begin{aligned} growth_{i,j,t} = {} & \sum_{L=0}^{n}\left[\beta_L \ x \ C_{i,j,t-L}\right] + \sum_{L=0}^{n}\left[\alpha_L \ x \ C_{i,j,t-L} \ x \ M_{i,j,t-L}\right] \\ & + \gamma_j + \delta_t + \left[\theta_{i,t}\right] + \eta X_{i,j,t} + \epsilon_{i,j,t} \qquad [2] \end{aligned}$$

to measure the storm protection services provided by mangroves, where *M* is an indicator of mangrove length from the coastal community's seaward edge computed as administrative unit *i's* average distance (in meters) of mangroves per meter of coastline. The vector of α coefficients mediates the impact of cyclone exposure on economic activity for increasingly distant mangroves from the community's seaward edge. Here, a vector of negative coefficients represents sheltering of economic activity in coastal communities by attenuating the cyclone's direct effect on the growth of luminosity. The net cumulative impact of cyclone exposure in year *t* on luminosity growth *z* years later is

$$\Lambda_{i,j,t} = \sum_{L=0}^{z}\left[\beta_L - \alpha_L M_{i,j,t}\right]$$

for a given mangrove width in the exposure year. For all specifications, we also include a *year x country* interaction to absorb year-to-year country-specific shocks in luminosity growth and a linear time trend to absorb country-specific background trends in luminosity growth.

We control for community-specific unobservable factors (*SI Appendix*, Tables S2 and S3) that may impact economic activity directly. For example, areas with geographically sheltered coastlines provide better habitat for mangroves and may also attract investment for coastal tourism. Further, we interact country and year fixed effects and exclude all provinces that do not contain mangroves. This interaction and sample selection criteria ensure that our results are driven by highly local variation in mangroves that are likely to share similar coastline features, general adaptability to weather shocks and other unobservable factors that may influence poststorm economic recovery in our treatment group of communities exposed directly to cyclones. We support this reasoning empirically by repeating our primary analysis on only Vietnam's coastal communities (*SI Appendix*, Fig. S1 and Tables S4 and S5). This subsample of our global analysis replicates, quantitatively and qualitatively, findings from our global analysis, which remains robust when excluding sheltered bays explicitly from the analysis. In fact, excluding sheltered bays from the analysis increases the measured role of mangroves in sheltering coastal economic activity because within-country variation in mangroves is not muted by local topography that might otherwise provide a blanket protection for a region's coastal communities. Globally, such a stringent definition of cyclone exposure and sample selection, alongside our conservative empirical specification, is likely to understate the actual role of mangroves in sheltering coastal economic activity.

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